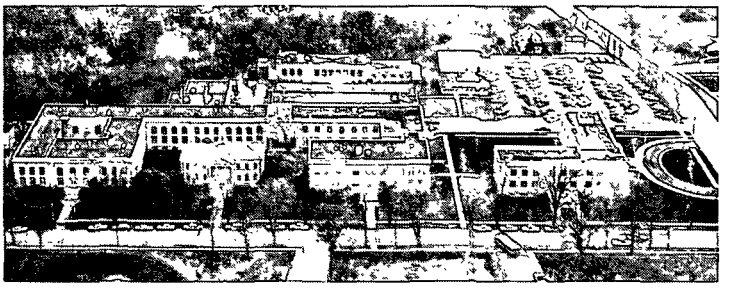

THE INSTITUTE OF PAPER CHEMISTRY, APPLETON, WISCONSIN

IPC TECHNICAL PAPER SERIES
NUMBER 240

SOFT X-RAY IMAGING CAN BE USED TO ASSESS SHEET FORMATION AND QUALITY

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JUNE, 1987

Soft X-Ray Imaging Can be Used to Assess Sheet Formation and Quality

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This manuscript is based on results obtained in IPC Project 3479, and is to be presented at the TAPPI Engineering Conference in September, 1987 in New Orleans

SOFT X-RAY IMAGING CAN BE USED TO ASSESS SHEET FORMATION AND QUALITY

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ABSTRACT

Low energy (< 10 keV) x-ray radiography can be used to assess paper sheet mass distribution (formation) with spatial resolution on the order of one fiber diameter. Digital image processing can be employed to quantify mass and floc size distribution via histogram analysis and two dimensional Fast Fourier Transforms, respectively. Issues regarding spatial variation of the x-ray field and reproducibility are discussed. It is proposed that superior speed and resolution may be achieved via optical image processing techniques.

In addition to true mass distribution measurement, the technique has several other advantages and potential uses. Formation can be assessed independently of sheet color. Stickies and other contaminants are easily quantified. The quality of internal layers in multilayer sheets can be assessed. These and other practical applications are discussed.

INTRODUCTION

A universally accepted definition of sheet formation and a fundamentally sound technique for its measurement on some absolute basis continue to be basic needs of the paper industry. For the purposes of this work we define formation as simply the in-plane mass or basis weight (g/sq meter) distribution. Ideally one would like to quantify not only the statistical variation of basis weight given some prescribed spatial resolution but also the spatial variation of mass (floc size distribution) itself. An easily applied technique to determine true sheet mass distribution with fine spatial resolution would be a powerful tool for assessing sheet quality as it would allow the comparison of products made under vastly different conditions on an absolute scale.

Current approaches fail to realize the objective of readily determined mass distribution on the fine scale. All optically based approaches rely on a scattering mechanism which is not a true measure of mass and can be sensitive to the presence of fillers and colorants. Also, these become more difficult to apply as basis weight increases. While the various optical schemes can be used to qualitatively rank sheets which are not vastly different, they fail to provide a true measure of density distribution and the different approaches have been shown to disagree in their rankings of identical sheets. Finally, the resolution of such devices is quite limited.

Therefore there exists a need for some technique for formation measurement meeting the following criteria:

1. A true measure of in-plane mass distribution
2. Ability to function over a wide range of sheet basis weights
3. Fine spatial resolution
4. Easily quantified results
5. Insensitivity to presence of additives, colorants, etc.
6. Fast, easy operation
7. Large sample size

SOFT X-RAY IMAGING

X-ray energies can be grouped as shown in Table 1. While x-rays are attenuated at all energy levels according to Eq. (1), the value of μ, the linear absorption coefficient, varies with energy and from material to material in a well documented fashion. More importantly, several mechanisms contribute to total attenuation as shown in Eq. (2).

$$I_{out} = I_{in}\, e^{-\mu l} \qquad (1)$$

where: I_{out} = x-ray intensity leaving sample
I_{in} = incident x-ray intensity
μ = linear absorption coefficient (cm^{-1})
l = sample thickness (cm)

$$(\mu/\rho)_T = (\mu/\rho)_A + (\mu/\rho)_S + (\mu/\rho)_{PP} \qquad (2)$$

where: ρ = density (g/cm^3)
(μ/ρ) = mass absorption coefficient
T = total
A = due to absorption
S = due to scattering
PP = due to pair production

Table 1. X-ray energy levels

	Energy (keV)	Wavelength (A)
Ultrasoft	0.12-1.2	10-100
Soft	1.2-12.0	1.0-10
Hard	12-120	0.1-1.0
Ultrahard	> 120	< 0.1

As energy increases, the relative importance of absorption, scattering and pair production varies. This is illustrated in Fig. 1 for the case of carbon. The usefulness of very soft x-ray imaging for formation measurement is based on the fact that absorption dominates scattering as the attenuation mechanism for carbonlike materials at energies below 10 keV.

This has two important implications. First, an image produced at such low energies must reflect the true mass present. Secondly, the relatively low level of scattering should give fine spatial resolution.

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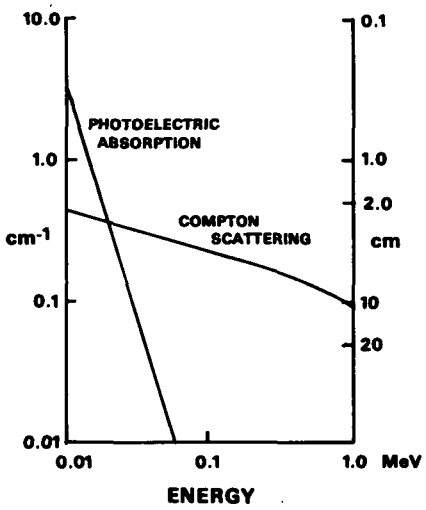

Fig. 1 Relative importance of x-ray absorption and scattering (carbon 1.5 g/cm^3).

While the theoretical possibility for directly imaging true mass distribution with fine resolution is appealing, the first question must be a practical one. Can such low energy imaging be conducted in reasonable times over a wide range of sheet basis weights? Initial experiments answered this question in the affirmative. Figures 2 and 3 show radiographs of commercial tissue and board samples. Conditions for these radiographs are listed in Table 2.

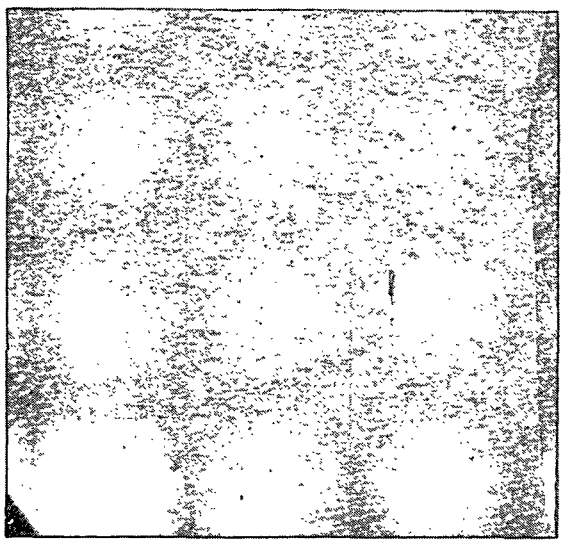

Fig. 2 Soft x-ray image of commercial tissue sample.

As the sheet samples are in intimate contact with the film, resolution is very fine. Tests with fine metal filaments show spatial resolution to be in the range of 5 to 10 microns with film uniformity being the limiting factor. All radiographs produced in this study were taken with a commercially available cabinet x-ray system (Hewlett-Packard Faxitron Model 43855A).

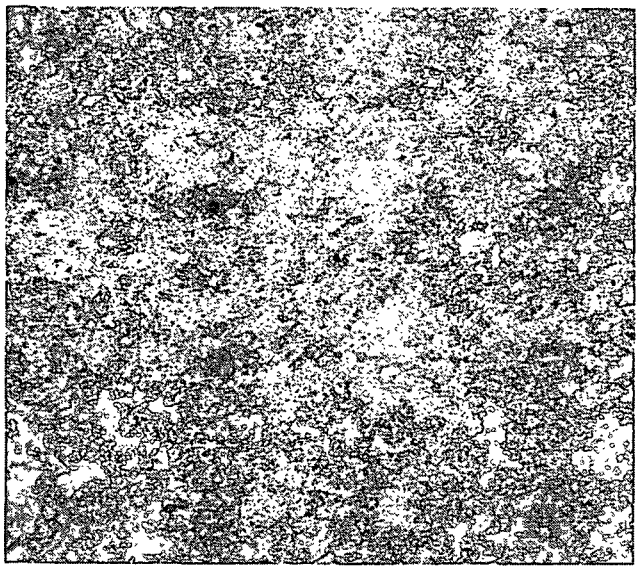

Fig. 3 Soft x-ray image of commercial board sample.

Table 2. Initial trials

	Sample 1 Fig. 2	Sample 2 Fig. 3
Film	Kodak LP7	Kodak Ultratec
Energy (kVp)	10	6
Developer	Kodak D-8	Kodak Ultratec
Developing time (min)	3.0	1.5

MEASUREMENT OF DENSITY DISTRIBUTION

To assess the utility of this technique for formation measurement a number of handsheets were produced on a standard former. Sheets were produced at basis weights of 60, 100, 150, and 300 g/m^2. At each basis weight sheet formation was varied by allowing the suspension to settle for times of 0 (standard), 30 and 60 seconds prior to sheet production. These sheets were pressed, air dried and analyzed for tensile strength, opacity and formation (Thwing-Albert). These results are listed in Table 3 and depicted in Fig. 4-6.

Table 3. Handsheet data

Sample No.	Basis Weight (g/m^2)	Settling Time (s)	Tensile Strength (kN/m)	Opacity (%)	Formation Index
60STD	60	0	5.13	69.1	92.1
60/30	60	30	4.47	69.6	45.6
60/60	60	60	4.47	70.3	29.4
100STD	100	0	8.23	82.1	79.8
100/30	100	30	7.71	81.0	45.9
100/60	100	60	7.77	83.4	36.2
150STD	150	0	12.9	89.5	72.3
150/30	150	30	10.7	89.6	44.7
150/60	150	60	11.2	90.3	35.9
200STD	200	0	15.8	93.9	69.2
200/30	200	30	12.7	93.7	42.2
200/60	200	60	12.5	94.1	36.1

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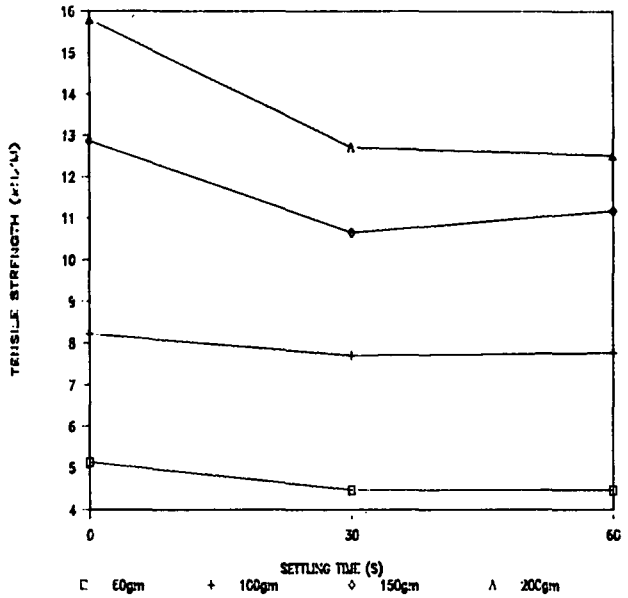

Fig. 4 Tensile strength vs. settling time and basis weight.

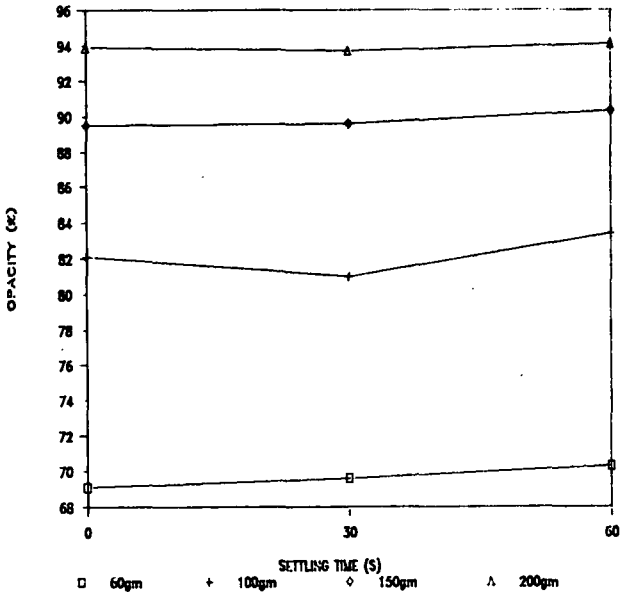

Fig. 5 Opacity vs. settling time and basis weight.

All samples were then imaged using the cabinet x-ray system. Processing conditions are listed in Table 4. A step wedge of 50 g/m^2 mylar sheets served as a calibration for each shot. Typical images are shown in Fig. 7 and 8.

Figures 9 and 10 show image intensity for the calibration wedge. All radiographs were reverse printed to give positives for image analysis. Analysis was performed on a Tracor-Northern image analyzer. Figure 9 shows the spatial variation of intensity across part of a wedge while Fig. 10 depicts the statistical distribution of intensity vs. basis weight. Intensity distributions have been normalized to give equal areas under the peaks corresponding to 100, 150, and 200 g/m^2 in Fig. 10.

The presence of a double peak at 150 g/m^2 indicates one of the fundamental problems with the technique. Due to the x-ray source "heel" effect shown in Fig. 11 there exists a significant variation of x-ray field intensity within the cabinet as shown in Fig. 12. While no attempt was made to account for this variation in the intensity data, its effect was minimized by studying relatively small samples at the maximum allowable source-to-film distance.

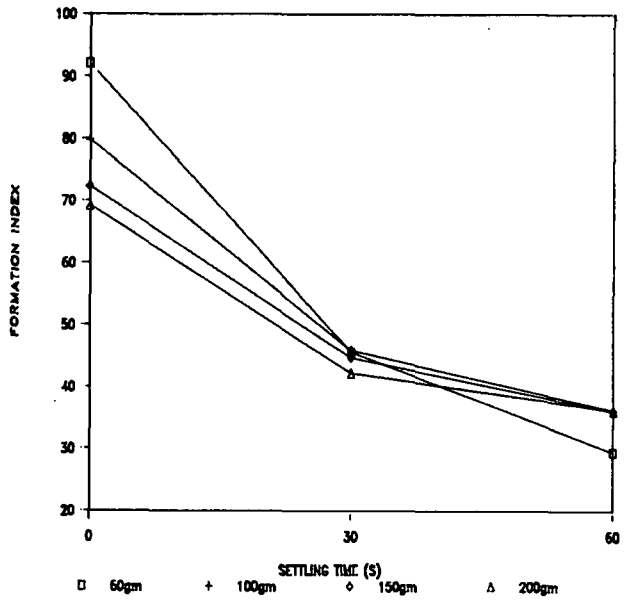

Fig. 6 Thwing Formation Index vs. settling time and basis weight.

Table 4. Film processing conditions

Film	Kodak LP7
Exposure time	60 min
Energy	8 kVp
Developer	EKtaflow Type 1
Developing time	2 min

The raw intensity distributions for samples 150STD and 150/30 are shown in Fig. 13. Sample fields of 3.75 x 3.75 cm were digitized with 512 x 512 resolution for spatial resolution of approximately 70 microns. Statistical data for these images and for a blank exposure of comparable average exposure are listed in Table 5. Variability in average intensity for samples of the same basis weight can be traced to exposure and manual processing variability, both of which can be eliminated if so desired.

The intensity histograms were normalized, translated to give equal average values and converted to basis weight histograms using the slope of the calibration correlation shown in Fig. 14. The resulting histograms and statistics are shown in Fig. 15 and Table 6, respectively.

3

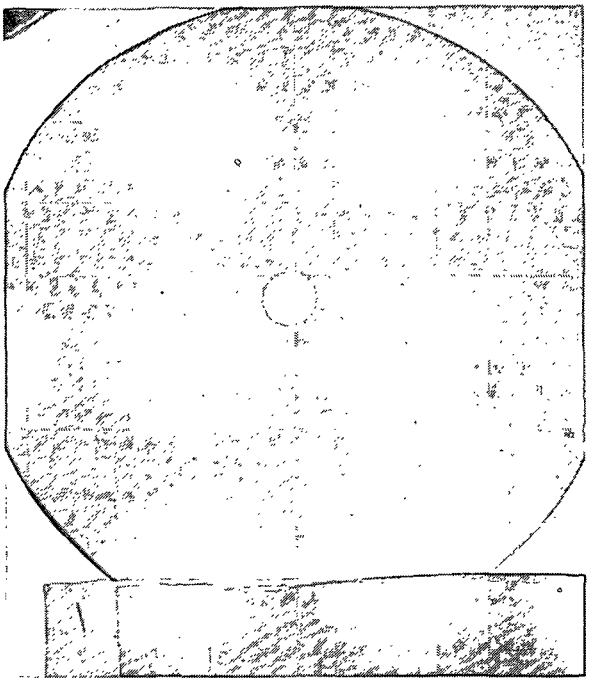

Fig. 7 Typical radiograph with calibration wedge (60STD).

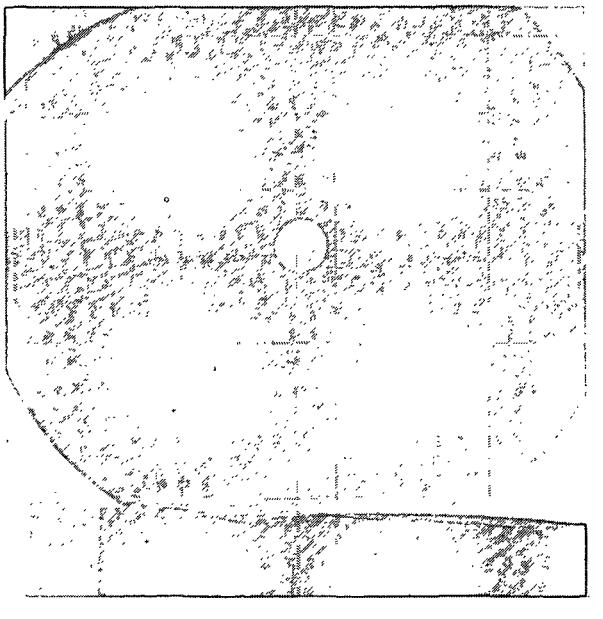

Fig. 8 Typical radiograph with calibration wedge (60/60).

Clearly, even with the problems of spatial variation of the x-ray field and sample-to-sample processing variations, soft x-ray imaging is capable of quantifying mass distribution when coupled with digital image processing. Spatial resolution is limited not by the imaging technique but by digital processing resolution.

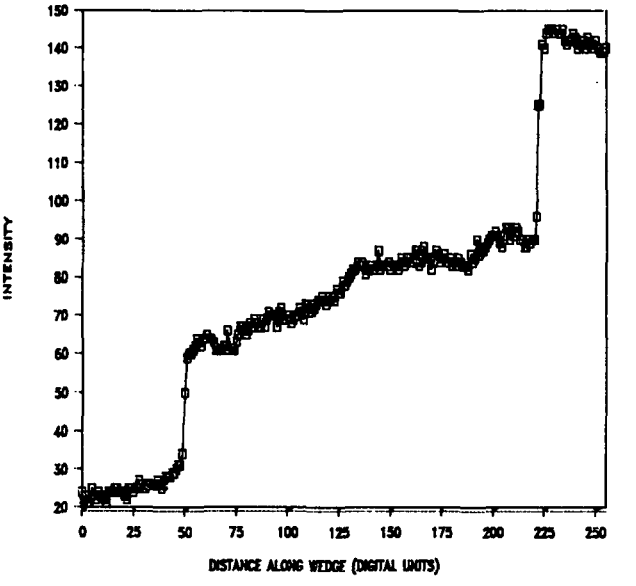

Fig. 9 Spatial variation of intensity in wedge.

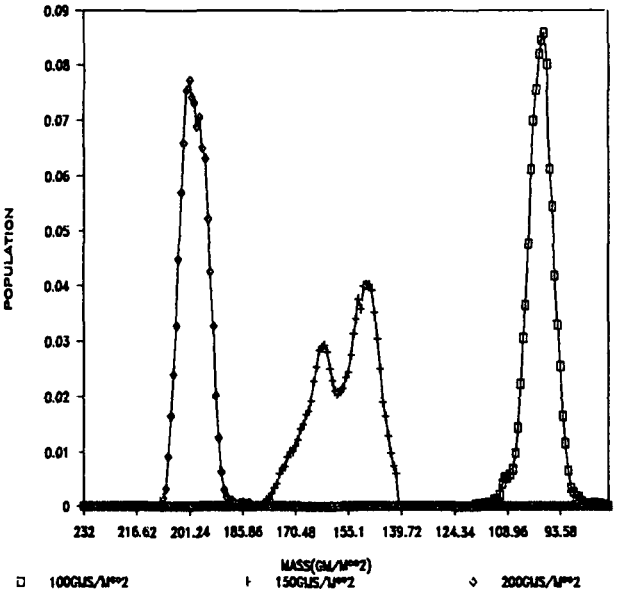

Fig. 10 Statistical variation of intensity in wedge.

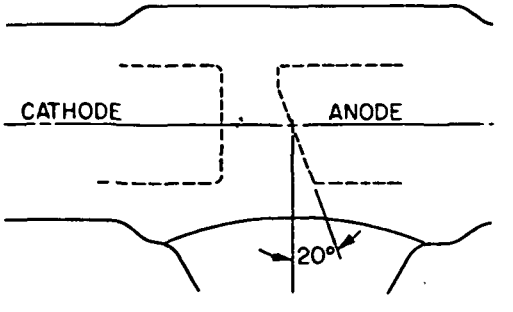

Fig. 11 X-ray source heel effect.

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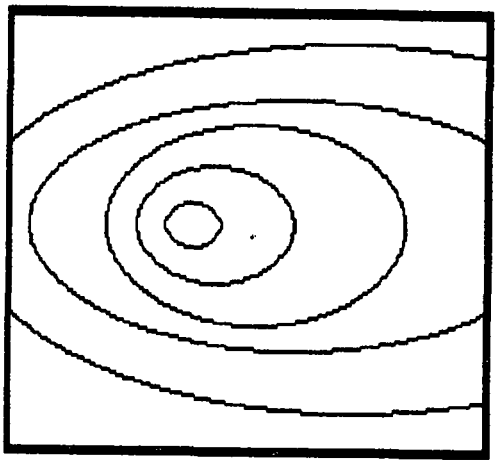

Fig. 12 Spatial variation of x-ray field intensity.

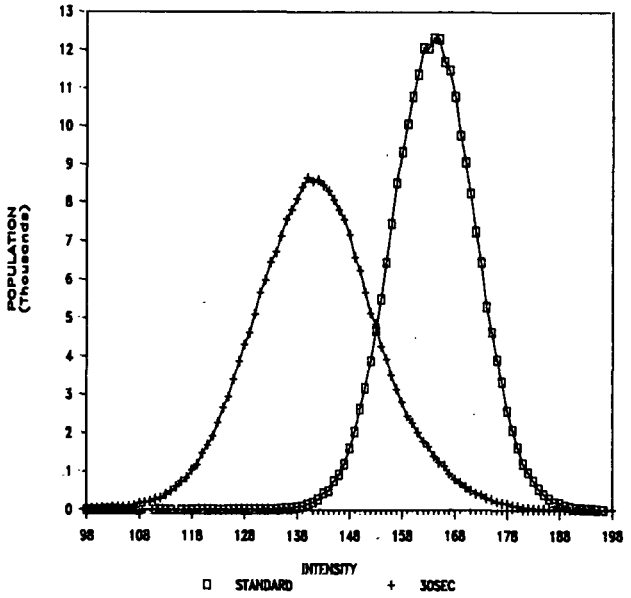

Fig. 13 Raw intensity distributions.

Table 5. Raw intensity data

	Blank	150STD	150/30
Average	153.0	164.0	141.6
Variance	17.9	65.0	144.1
Std. Dev.	4.2	8.1	12.0

FLOC SIZE DISTRIBUTION

While the statistical distribution of sheet density is important, at least as important is some measure of its scale of spatial variation as it relates to floc size distribution. To assess spatial periodicity of density distribution the samples just discussed were analyzed via two dimensional Fast Fourier Transforms (FFT). The 2-D power spectra for samples 150STD and 150/30 are shown in Fig. 16 and 17. The broad power spectrum observed in Fig. 16 is indicative of the very fine structure (high frequency variations) dominating the well formed sample while the more compact spectrum of Fig. 17 can be attributed to the large scale variations (floc structure) present in the less even sample.

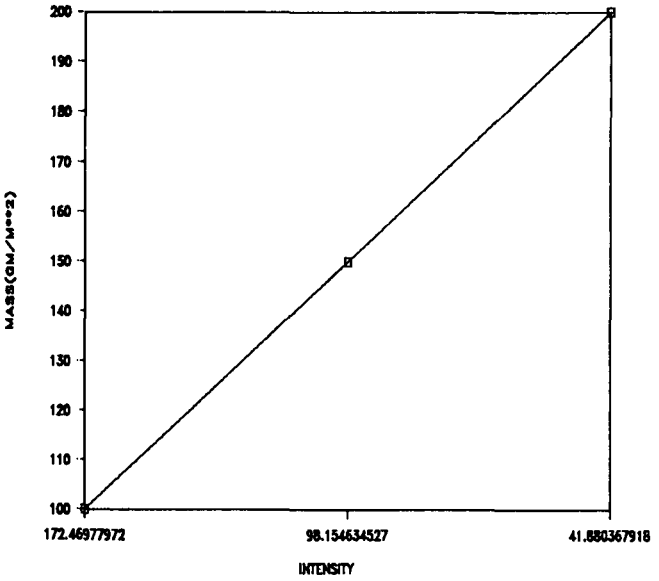

Fig. 14 Mass vs. intensity correlation.

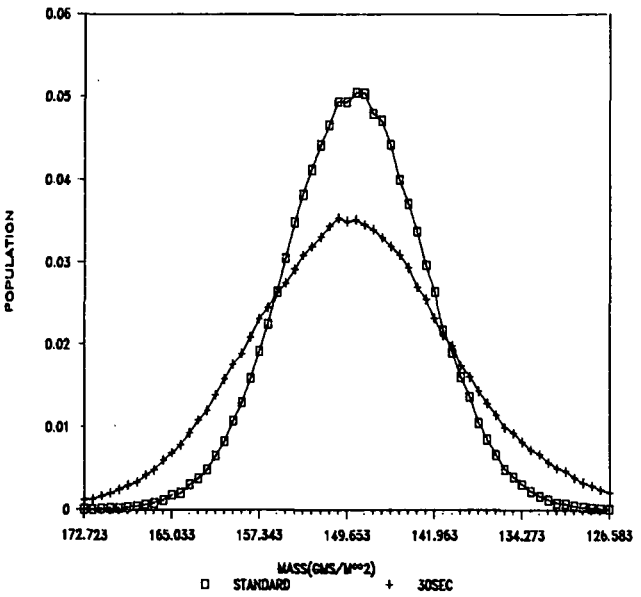

Fig. 15 Normalized basis weight distributions.

Table 6. Normalized basis weight distributions

	150STD	150/30
Average	148.9	150.1
Variance	38.5	85.2
Std. Dev.	6.2	12.3

5

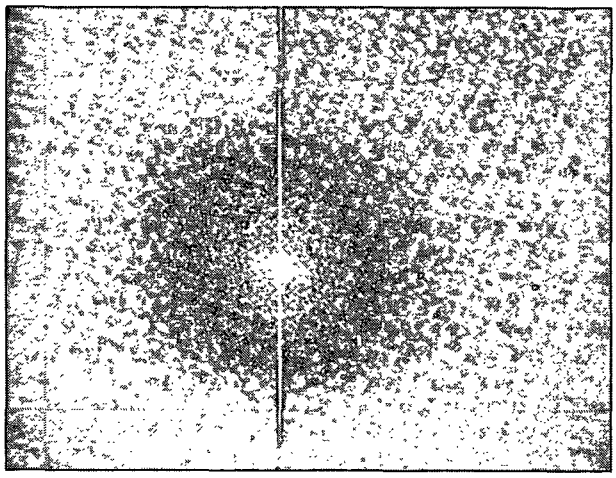

Fig. 16 2-D power spectrum (150STD).

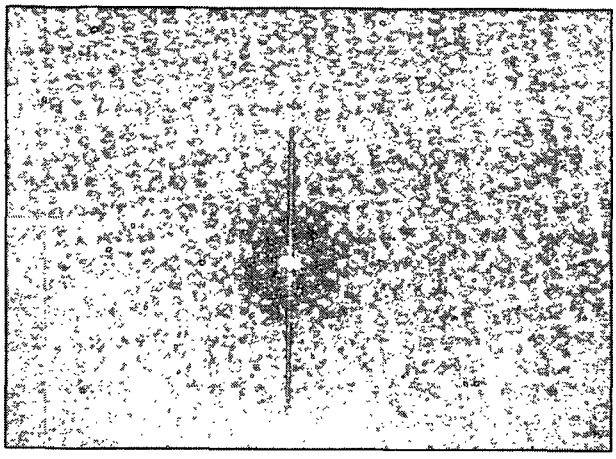

Fig. 17 2-D power spectrum (150/30).

While it is difficult to correct for the spatial variations of the x-ray field in physical space, it is relatively simple to account for them in Fourier space as they superimpose very long wavelength variations on the image. Figures 18 and 19 were obtained by subtracting the power spectrum of the blank exposure from those of the two sheet samples. Note that Fig. 19 has been magnified 3X now. Again the broader spectrum is indicative of finer structure in the sample. Some measure of this breadth, such as half height width, can be used to "put a number on" this indicator of floc size distribution.

SUMMARY OF FORMATION TESTS

The main objective of these tests was to determine if very soft x-ray imaging can serve as a practical tool to assess sheet density and floc size distribution. Difficulties were encountered which can be traced to the variability in x-ray field intensity and processing. During the course of this work, the author became aware of the efforts of Yuhara (1) and Hasuike (2) in the same area. It can be shown that x-ray field intensity variations can be corrected for by digitizing a blank image and using it in a pixel-by-pixel correction scheme. While it has been shown that state-of-the-art image analysis can be employed to obtain quantitative data on both density and floc size distribution, one must question the availability of such tools to those most interested in measuring sheet quality. The answer may be found via optical image processing. Most of the computations performed digitally in this study can be executed via relatively inexpensive optical techniques at much greater speed and finer resolution.

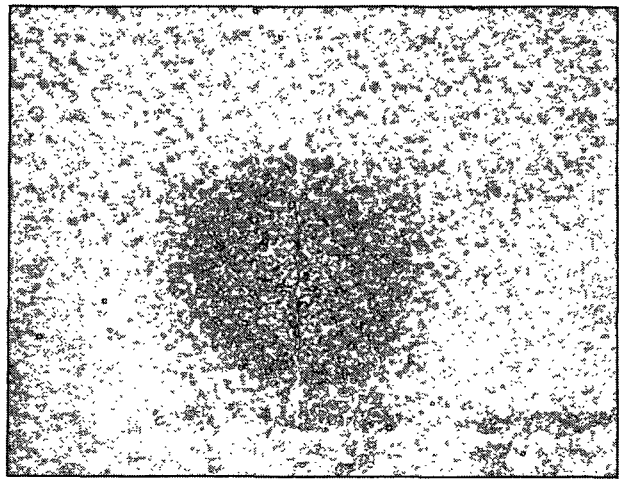

Fig. 18 2-D power spectrum (150STD minus blank).

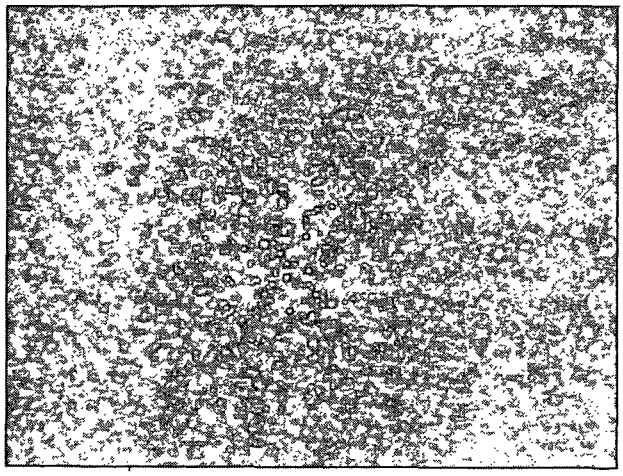

Fig. 19 2-D power spectrum [150/30 minus blank (at 3X)].

OTHER FEATURES OF VERY SOFT X-RAY IMAGING

Any optically based formation tester must be very sensitive to the presence of fine particles, additives and colorants in particular. Since these materials are usually present at low levels on a mass basis, a true density distribution measurement such as soft x-ray is not significantly disturbed.

Low energy x-ray imaging can be used to monitor contaminant levels. Figure 20 clearly identifies the particles contaminating a piece of pseudoboard and the resulting image can be easily processed digitally to obtain particle size distribution data.

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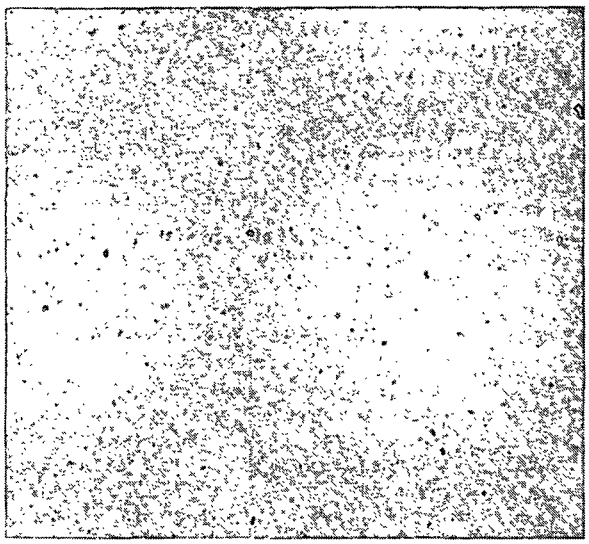

Fig. 20 Soft x-ray image of pseudoboard sample.

While all images produced in this study employed a cabinet x-ray system and exposure times on the order of seconds to minutes, it is possible to obtain images at speeds which make on-line measurements at least feasibile. Figure 21 is a flash x-ray radiograph of the pseudoboard sample. Some resolution and contrast are lost relative to the cabinet pictures as the effective energy level is approximately 20 keV. However, the flash image exposure time was 70 nanoseconds.

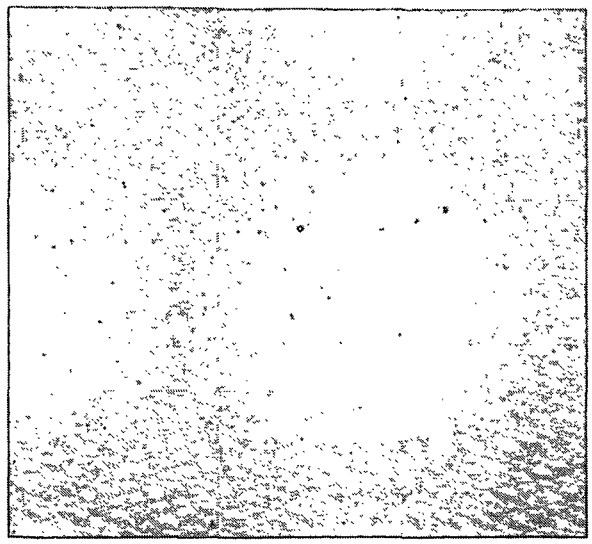

Fig. 21 Flash x-ray image of pseudoboard.

ACKNOWLEDGMENTS

The support of the members of The Institute of Paper Chemistry is greatly appreciated. The author also thanks the Hewlett-Packard Company (McMinnville Division) and Tracor-Northern Inc. for the use of their equipment in this exploratory study.

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2. Hasuike, M., private communication.

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